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Author(s): W. D. Stanbro, C. A. Rodriguez, C. T. Olinger, and T. L. Cremers

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EVALUATION OF THREE NEW TECHNOLOGIES FOR INTERNATIONAL SAFEGUARDS*

W. D. Stanbro, C. A. Rodriguez, C. T. Olinger, and T. L. Cremers
Los Alamos National Laboratory
Los Alamos, New Mexico 87545, USA

Abstract

Los Alamos National Laboratory is examining a number of promising technologies that could increase the effectiveness and efficiency of international nuclear safeguards. The techniques described in this paper include video image processing, infrared imaging, and acoustic resonance spectroscopy. Each of these techniques offers unique advantages in the implementation of an inspection regime.

1. Introduction

International safeguards inspections must be carried out as efficiently and effectively as possible. To this end, the Los Alamos National Laboratory Safeguards Program is always evaluating new technologies that might improve safeguards inspections. We are currently investigating applications of three technologies to safeguards: video image processing, infrared imaging, and acoustic resonance spectroscopy. These three technologies vary in technical maturity and the extent to which they have been tested in the safeguards environment. In the following sections we will describe the hardware and software that compose these systems as well as some of their applications to safeguards.

2. Video Image Processing

Concept

Video image processing has emerged as a technology that shows promise for the safeguarding of nuclear materials. In abstract terms, we use image data to establish a known state for a given area; subsequent image data can then be evaluated to provide information regarding physical and environmental changes in the area. The image data can be in a wide variety of formats and can be analyzed to determine predefined alarm conditions or simply compressed using digital compression methods for review at a later date.

The Safeguards Program at Los Alamos National Laboratory has been developing an image based materials verification system that provides timely information about the state of nuclear materials in storage or in process. The Experimental Inventory Verification System (EIVSystem) uses image processing technology to acquire "basis" information about materials being monitored. From this basis, change detection, image processing, and image analysis methods are applied to detect changes, or events, in the monitored area. Detected events can be analyzed to determine their safeguards significance, retained for the historical record or ongoing analysis, and used to trigger alarms that bring the event to the immediate attention of operations or protection personnel[1]

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Hardware

The EIVSystem is designed to run on commercially available computer systems to provide maximum performance, reliability, and maintainability while taking advantage of the newest designs in the rapidly developing computer industry. An EIVSystem usually consists of a Sun Microsystems SPARC station 10 with a single cpu as the host computer equipped with system and data disks, CD-ROM, up to 512MB random access memory, and a tape unit for archival storage. High performance applications of the EIVSystem can take advantage of multi-processor options that allow true parallel processing. Data capacity can vary from 1 to 5 gigabytes, depending on the system application. Camera inputs can vary from 2 NTSC format inputs plus 1 Svideo input to 16 NTSC inputs plus 8 Svideo inputs.

Software

The EIVSystem software has been developed specifically for nuclear safeguards applications. Unlike many commercially available surveillance systems, the EIVSystem is designed to address the specialized needs of the nuclear safeguards community. The current model of the EIVSystem includes an X-Window based user interface featuring "point and click" selection for all system functions, a C2 operating system and additional mandatory and discretionary access controls, a system administration tool, an event logger, a camera configuration tool, a camera controller, a data disk controller, a report generation tool, an interactive image analysis tool, and an alarm manager. A C2 level operating system provides overall computer security features for the host computer, while mandatory and discretionary access controls, set by the system administration feature, provide security for the application software itself. Event logging is used to record the actions of users who have successfully logged into the surveillance system as well as to record events detected by the system's image processing software. The camera configuration mechanism allows the user to interactively create a graphic model of the surveillance area and place cameras in the model relative to their actual location. Each camera is then interactively configured by assigning values for various camera parameters. These parameters may include thresholds, detection sensitivities, and camera types (for example, detection and video). The camera controller is used to activate the surveillance once the camera configuration is complete. The user controls the data disks through the EIVSystem interface, this isolates the user from the host computer's operating system. Data can be archived to tape from the system's 1.05 gigabyte data disk(s) once the data have been reviewed, leaving the system ready to accept new surveillance data. The EIVSystem can automatically archive data to tape as well. At configurable intervals, the system will automatically copy all new data onto a 5-gigabyte, 8-mm tape.

The report generation tool in the EIVSystem allows the user to produce formatted versions of system logs in DOS or UNIX files that can also be printed directly from the system user interface. The system will generate access, error, operation, and alarm logs as well as logs consisting of statistical information such as "How many alarms this month?" or "How many system logins this period?" A report feature allows the use of site specific report templates for producing periodic reports summarizing system performance.

For data analysis and for live video viewing, the EIVSystem provides an interactive image analysis tool. Difference data collected over a period of time are presented to the user in chronological order for review. For example, if vault doors were opened four times during a month to perform "alarm checks," the collected data would include time stamped images representing these vault accesses (see Fig. 1).

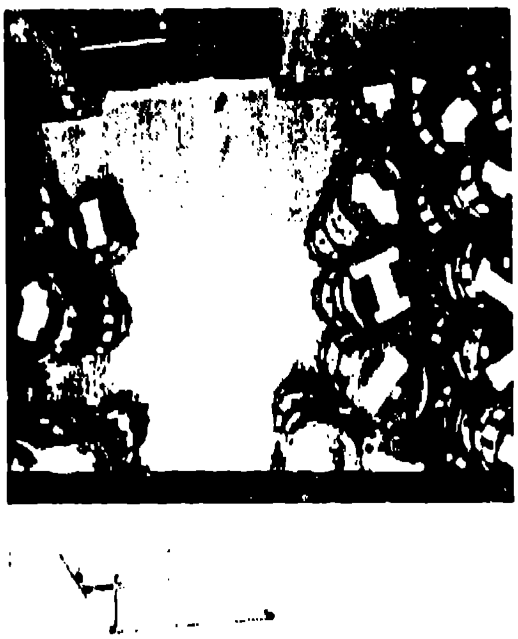

Fig. 1 Top: vault when secured. Bottom: data resulting from the opening of vault doors for an alarm check.

Where a detected event triggered the collection of video data, the video data are presented to the user in an animation sequence that can be replayed at a user-selectable speed. Image data can also be manually differenced using the image tool, providing the ability to verify correct functioning of the system's image processing software or to analyze total change from one date to another. The gross change in an area could be analyzed, for example, by comparing a June 1st image with an August 1st image.

The alarm manager provides an interface to the particular alarm mechanism configured into the EIVSystem installation. A system configured for data gathering only would interface to alarm and event logs. For systems that are configured with audible and visible alarms, the alarm manager would provide on, off, and reset functions. Or the alarm manager may activate the alarm relay when the EIVSystem is installed to interface with existing facility alarm systems.

Applications

Currently the EIVSystem is installed at two US Department of Energy sites to reduce the frequency of physical inventories. In this application, basis imagery is recorded for each vault camera and the EIVSystem is activated with the vault doors secured. Continuous monitoring of the vault is then automatically performed until the cameras are deactivated by an authorized user. In secure mode the EIVSystem expects no entry to the area and will alarm on detected events such as entry by facility personnel as is shown in Fig. 2.

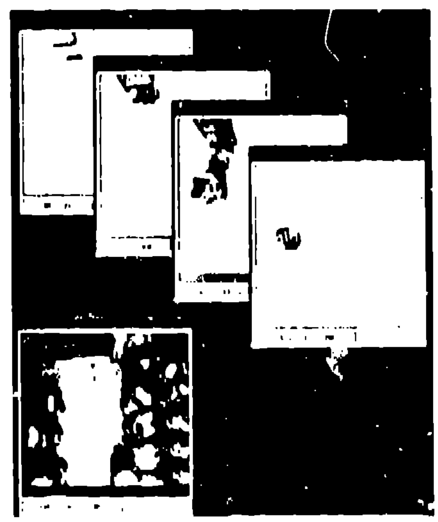

Fig. 2 In this sequence of data, the vault door (top left) is opened, a human enters carrying an object, places the new object in the vault, and leaves the area. The new object is shown as a difference (lower right).

In access mode the EIVSystem would detect the opening of the door, would record the above entry data, but would not produce an alarm. The video recording feature of the EIVSystem can be activated to record the authorized vault access as well. The video data, coupled with difference images showing the net change resulting from the authorized access, provide a complete record of the vault access.

In another application of the EIVSystem, where the system is used for data gathering and review, software is configured such that a detected event will trigger the video recording system, storing compressed video data until the detected activity ceases. For example, a process area being monitored may contain instruments whose readings are recorded daily. When entry is detected, the video recording is activated. When personnel leave the area, the video and difference data are stored for later review. The video data provide a concise record of only the access period, saving storage media and simplifying the review process, while the difference data show if any sensitive items in the area may have been disturbed during an otherwise authorized access.

In either application, an EIVSystem region of interest feature currently under development will provide additional flexibility in monitoring an area for safeguards events. Using the region of interest feature while configuring individual cameras will allow the user to define "red," "yellow," and "green" zones within the camera's domain. Any entry or penetration into a red zone will generate an audible and visible alarm or could trigger video recording at a high frame rate. An entry into a yellow zone may trigger a "soft" alarm and video recording at a lesser frame rate, while entry into a green zone, a zone where we expect occasional activity, will only generate a time stamped data entry showing that access has occurred. Figure 3 shows an image that can be divided into regions of interest.

Fig. 3. A camera view that could be divided into zones.

Certain pattern recognition tasks can also be initiated when an event is detected to help the system assess and respond to alarms. For example, in Fig. 3 the doorway may be configured as a green zone, the central walkway as a yellow, and the container area as a red zone. If the vault doors are opened to perform an alarm check, rules for the green zone are applied: time stamped difference data are stored noting that access. Pattern recognition on this data serves to verify that the expected action occurred. If activity is detected in the walkway, video recording is activated at a low frame rate. Pattern recognition applied to this data can differentiate between a human walking in the yellow zone and a container that has fallen from its resting place.

3. Infrared Imaging

Concept

Infrared imaging extends the ideas behind normal video imaging to a new part of the electromagnetic spectrum. In addition to information on position, infrared images contain information on an object's temperature that is indicative of heat generation /1/. At Los Alamos we have been principally concerned with the observation of containers of plutonium /2/. However, similar principles will apply to any radioactively heated objects such as spent fuel assemblies.

Heat is generated by plutonium as a result of its radioactive decay. The actual amounts depend on the isotopic ratios, but for reactor grade material the thermal power generation is on the order of 15 W/kg. This heat generation is now commonly exploited in conventional calorimetric measurement systems /3/. When this material is placed in a container, the resulting rise in the surface temperature results in some of the energy being radiated as electromagnetic radiation in accordance with Planck's equation,

$$M_\lambda = \frac{2\pi c^2 h}{\lambda^5} \frac{\epsilon_\lambda}{e^{hc/\lambda kT} - 1}$$

where M_λ is the spectral radiant exitance, λ is the wavelength, ϵ_λ is the spectral emittance at that wavelength, c is the speed of light, h is Planck's constant, k is Boltzmann's constant, and T is the absolute temperature. For objects near room temperature, the wavelength of the peak emission is around 10 μm, which is in the infrared part of the spectrum. This wavelength is particularly convenient in that it corresponds to a window in the atmospheric absorption of infrared radiation. This minimizes the attenuation of the radiation before reaching the detector.

As can be seen in the Planck equation, the emission is a function of the spectral emissivity ϵ_λ as well as the temperature. Although emissivity is a function of wavelength, it is a weak enough function that it can be taken to be constant over most working wavelength intervals. In general, very smooth, shiny surfaces have low emissivities and reflection dominates over emission. Conversely, rough surfaces have high emissivities and are good candidates for infrared thermography. Fortunately, it is quite easy to modify an area of a surface to have a high emissivity. In our work we have used paper and thin cardboard labels as well as various types of tape. Anodized aluminum has also proven to provide an excellent high emissivity surface.

Hardware

Currently commercial equipment is readily available to provide both a real time video of the infrared emissions of objects and an estimate of their surface temperature. The instrument currently in use at the Los Alamos Plutonium Facility is an Inframetrics Model 760 Infrared Imaging

System. The system uses a scanned HgCdTe detector with an integrated cooling system that keeps the detector at 77°K. The integrated cooling system avoids the usual requirement for liquid nitrogen to cool the detector. The spectral band pass of the system is 8 to 12 μm. The system is quite portable and can be run off either batteries or wall current. The noise equivalent temperature difference is less than 0.2°C (less than 0.05°C with image averaging) at the temperature range of interest here. The images obtained by the system can be displayed either as gray scale or false color maps of the surface temperature. Built in software allows for averaging temperatures over time or sub areas of the image. Images can be saved on video tape or disk.

Applications

Applications of infrared imaging can be placed into two groups. The first of these is surveillance of containers of nuclear material. In this application the infrared emissions of a container provide a signature in addition to position that would have to be forged to prevent detection of a diversion. Figure 4 shows a thermogram of several anodized aluminum containers holding different sizes of ^{238}Pu heat sources. The heat sources shown are 3.8, 5.2, and 11.4 W. A fourth container with a heat output of 0.7 W is not visible at this scale setting (10°C full scale). Recorded images can be analyzed using the same software as described above for video image processing. In addition to changes in position, the thermograms also will indicate whether or not the surface temperature of an object has changed. Although some changes due to different ambient temperatures are to be expected, large changes over a short time could indicate a diversion of material.

Fig. 4 Thermogram of three anodized aluminum containers holding ^{238}Pu heat sources

The second type of application involves a semi quantitative confirmation of the mass of plutonium in a container. The temperature of the surface of a container, as determined with the infrared imaging system, has been found to be proportional to the amount of plutonium in the container. An example of this relationship is shown in Fig. 5. These semi quantitative determinations are discussed in more detail in an accompanying paper in this proceedings, "Measurement of Nuclear Materials by Infrared Imaging," by T. L. Cremers, W. D. Stanbro, and G. M. Kelley.

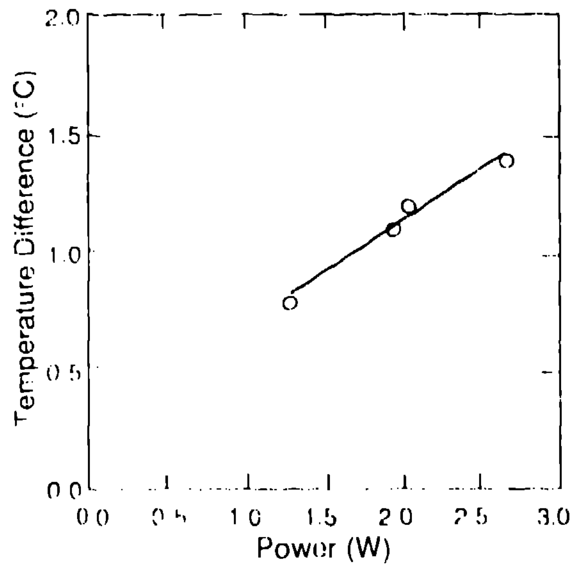

Fig. 5 Relationship between container surface temperature and thermal power output for plutonium oxides.

4. Acoustic Resonance Spectroscopy

Concept

The last technology to be discussed is acoustic resonance spectroscopy (ARS). ARS is a nondestructive evaluation technique developed to acoustically interrogate solid objects and containers. The technique evaluates acoustic spectra rapidly, inexpensively, and non intrusively and is field portable /4/.

All solid objects have natural modes (frequencies) at which they can vibrate relatively freely. These natural vibrational frequencies and their sharpness, or Q values, strongly depend on the physical characteristics of the body such as its size, shape, and the acoustic velocity in the material as well as stresses placed on the body. Even the simplest shapes have many natural modes that may be harmonic overtones of a primary mode (such as in a guitar string) or non harmonic overtones (such as for a drum head). Predicting the natural vibrational modes becomes increasingly difficult as the shape and complexity increases. Although analytically predicting the spectrum of complex shapes is time intensive even with computers, such acoustic spectra can be rapidly and easily measured.

When containers are filled with solids, liquids, or gas, the physical properties of the contents influence the container's acoustic characteristics. As the level of fluid in a water pipe increases, so does the pitch of sound. The increase in pitch reflects a change in the principal vibrational mode. Detailed spectral analysis of the sound reveals more subtle vibrational responses to the fluid density, viscosity, and acoustic velocity. Similarly, acoustic coupling between a container and its solid, liquid, or gaseous contents alters the acoustic response of the system. Some of the physical parameters influencing acoustic response are the geometry, physical characteristics, orientation (in the case of liquid- and solid-filled containers), occupied volume, and fill level of the container; fluid density, acoustic velocity in the fill material; fluid viscosity; contamination (suspended particulates); solution concentration; and the grain sizes of solid contents.

When simple and well defined geometries are considered, some of these parameters can be analytically deduced from a measured spectrum. For example, the fill level and acoustic velocity of a liquid in a cylindrical container could be determined if the response were numerically modeled. This would require significant expenditures of both personnel and computer time, and many container geometries are too complex to permit detailed computational analysis.

Selected parameters can also be determined if spectral relationships are known empirically for a selected container geometry and known fill type. Returning to our example of a water pipe, the pitch can be calibrated against the fill level; then the fill level can be deduced from the measured primary frequency. Theoretical treatment of this simplified example would be just as straightforward, but the empirical approach is more practical for more complicated geometries. Although acoustic spectra depend on many variables, an advantage of ARS is that various portions of the spectrum respond to different variables.

ARS excites a body at discrete acoustic frequencies, listens for the response at that frequency, and then steps to another frequency. Each step is close to the next in frequency and time, so the desired frequency range can be swept in just a few seconds. Advantages of this technique are that the excitation amplitude at each frequency is equal, ambient noise is filtered out if it is not in the narrow band width being measured at that step, and the acoustic spectrum can be displayed in real time. Figure 6 shows schematically the relationship of the applied acoustic signal and the response spectra.

Although the entire spectrum contains useful information, many applications depend only on the resonant frequencies and not their relative amplitudes or Q values. This eliminates the need to put the transducers at the same location on the container for each measurement and improves the applicability of the technique in the field where precision placement would be extremely difficult. Relative amplitudes may vary from one measurement to the next, but the measured resonant frequencies will be invariant unless a transducer is close enough to a particular node to prevent detection of those vibrations. Non detection of a single, or even a few, resonant frequencies should not significantly harm the analysis because multiple resonances are generally considered.

Hardware

The ARS system used for this study is based on an IBM/PC with a 80386 processor, but any similar hardware can be used. This system supports a single commercially available plug in board (DSA 100), which generates the

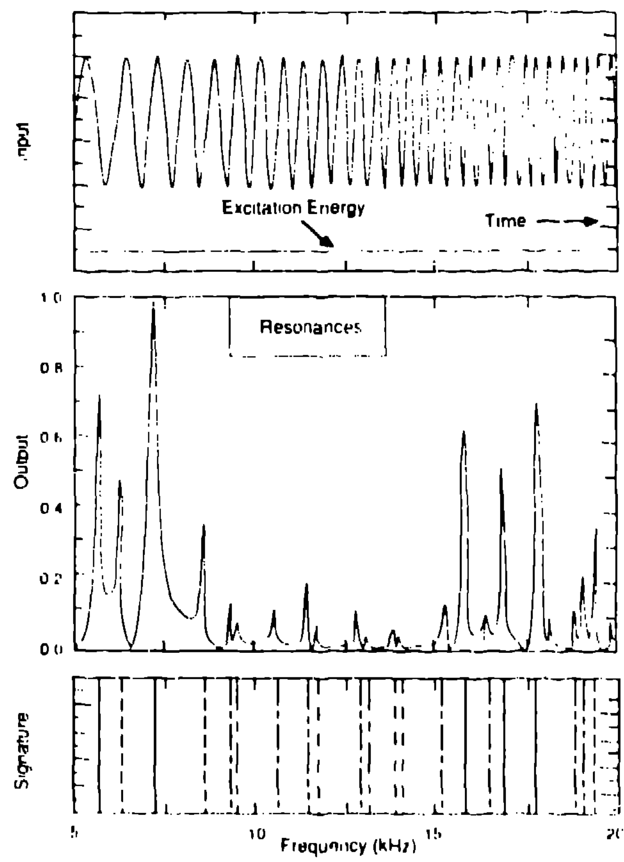

Fig. 6 Relationship between the applied acoustic signal and the response spectra. The top is the applied acoustic signal, the middle is the response spectra, and the bottom is a display of just the response frequencies.

input and analyzes the return signal. Alternatively, the DSA 100 board can be placed in a small box containing a rechargeable battery pack and programmed from a notebook type computer through an RS 232 interface. This increases the portability of the system. A pair of transducers completes the ARS system. One energizes the body being analyzed and the other detects the vibrational response, feeding the signal back to the DSA 100. The DSA 100 is accompanied by software necessary for data acquisition and graphical display, and the entire system can be procured for a few thousand dollars. A variation of this hardware is shown schematically in Fig. 7. In this case, excitation is achieved by a speaker driven by the computer and the vibrational response is detected by a laser vibration sensor. Such a system could be used for remote analysis where radiation fields may be high or where a large number of items need to be monitored in an automated mode.

Applications

ARS has many potential applications in safeguards. All of these applications still require development, but development directed toward similar and related applications has been performed in a few cases /5/

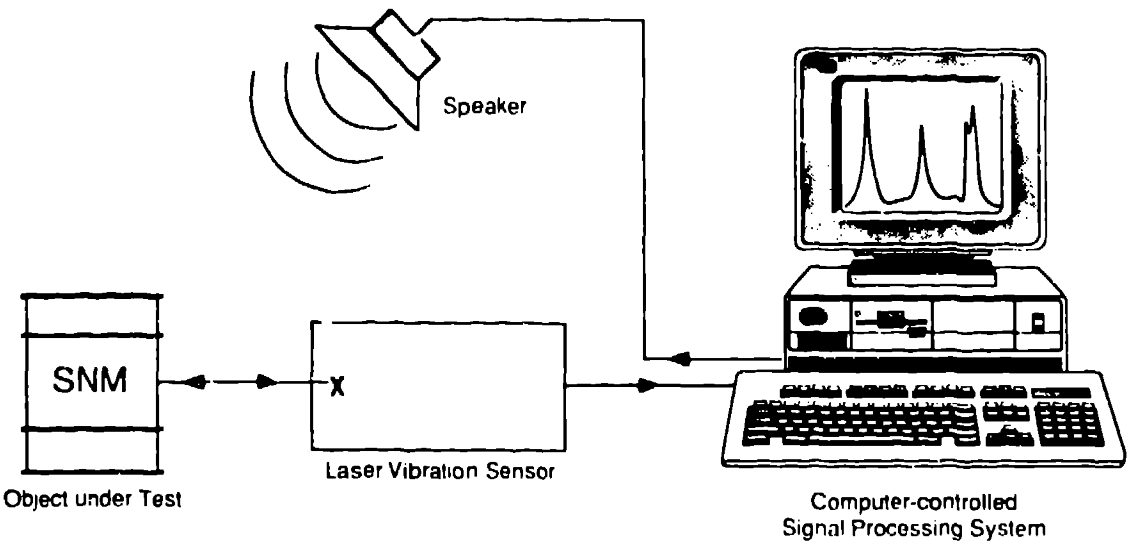

Fig. 7 The remotely monitored ARS system.

Candidate ARS safeguards applications include establishing and monitoring intrinsic tags and seals (that is, seals that establish the integrity of a container and its contents, not just the container itself); assessing fill levels of processing tanks or containers; detecting concealed compartments within larger containers; nondestructively analyzing material composition or solution concentrations; verifying processing system configurations (for example, valve positions or open diversion paths); and detecting holdup /6/.

5. Conclusions

In conclusion, new technologies with apparent applications to international safeguards appear constantly. The work to date on the three technologies considered here indicates that they may have significant safeguards applications. In each case the adoption of the technology by an operating facility will depend on the definition of an application in which the technology makes a difference and on the ability to engineer a reliable system that can be integrated with the facility operations.

Of the three, the video image processing is the most mature. The concept of operation is well understood and considerable work has gone into the configuration of the hardware and software to make the system more convenient for the user. Video image processing systems developed at Los Alamos are in use at two US nuclear facilities. The system was installed as a way of limiting the inventory frequency and the accompanying cost and radiation exposure.

Experience with the infrared imaging system has demonstrated that in particular cases it can be used to supplement more traditional imaging technology. Under the appropriate conditions, infrared imaging adds another dimension to surveillance by providing information on the contents of containers as well as the position. It is still necessary to perform the detailed engineering necessary to fit infrared imaging into a production environment.

Based on a number of initial applications of ARS in other areas /4/, we believe ARS will be of great utility in safeguards. We are still in the initial phases of exploring a number of safeguards applications for this promising technology.

References

/1/ W. D. Stanbro, R. S. Leonard, C. A. Steverson, and M. L. Angerman, "A Survey of Infrared Technology for Special Nuclear Materials Control and Accounting," LA-12241-MS, March 1992.

/2/ W. D. Stanbro, R. S. Leonard, M. W. Johnson, T. L. Cremers, and S. W. Moore, "Proof-of-Principle Investigations on the Application of Infrared Technology to Safeguards," LA-12288-MS, April 1992.

/3/ R. Likes, "Principles of Calorimetric Assay," in *Passive Nondestructive Assay of Nuclear Materials*, D. Reilly, N. Ensslin, H. Smith, and S. Kreiner, Eds., NUREG/CR-5550, March 1991.

/4/ D. N. Sinha, "Acoustic Resonance Spectroscopy (ARS)," *IEEE Potentials* **11**, 10-13 (1992).

/5/ D. N. Sinha and K. E. Apt, "Acoustic Resonance Spectroscopy," in *Verification Technologies*, Department of Energy/Office of Arms Control and Nonproliferation, DOE/DP/OAC/VT-92A, 1992.

/6/ C. T. Olinger, W. D. Stanbro, M. F. Mullen, and D. N. Sinha, "Potential Acoustic Resonance Spectroscopy Applications Satisfying Needs in Nuclear Safeguards," N-4/92-1401, December 1992.